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Resistance of Samarium-Cobalt
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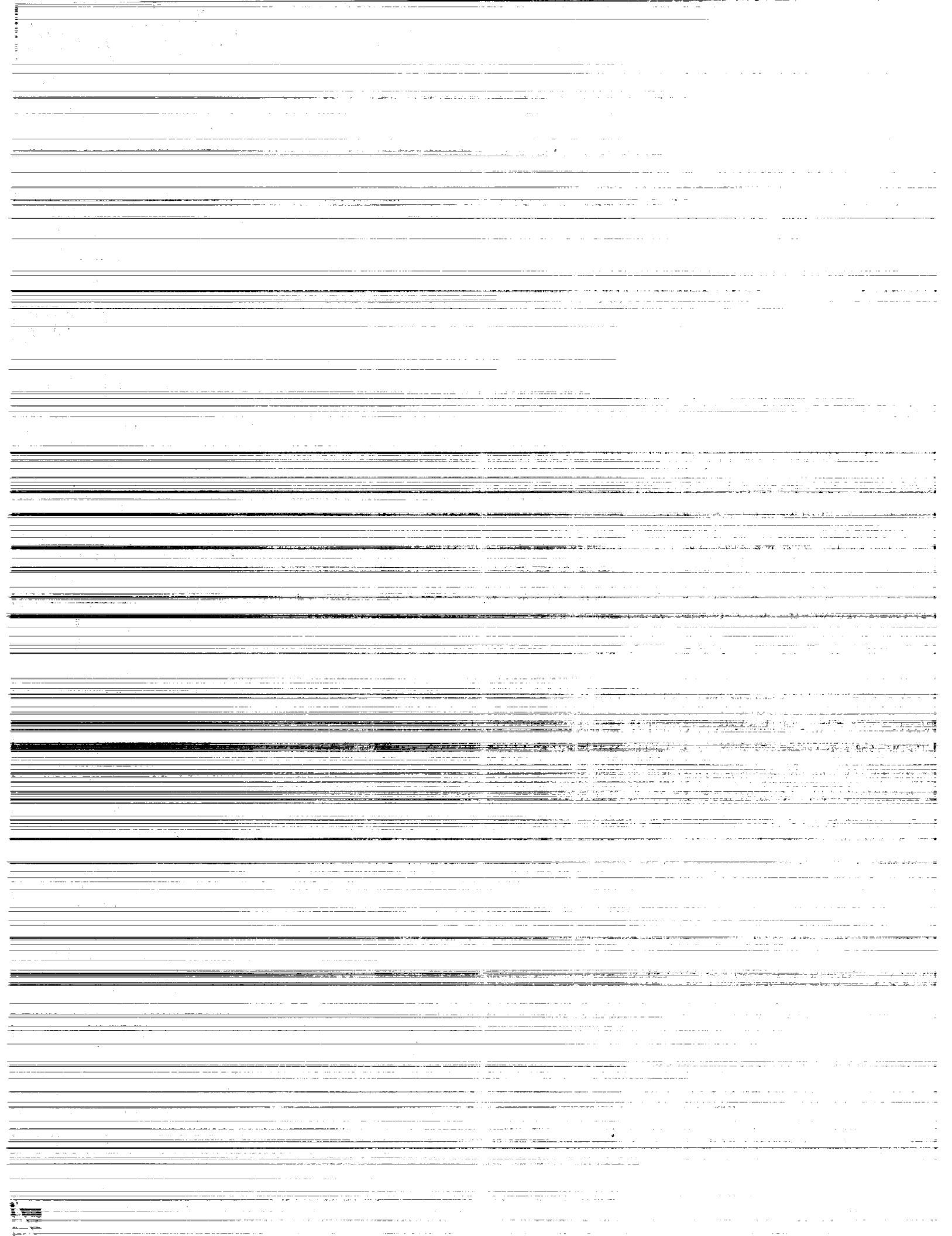
Janis M. Niedra
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National Aeronautics and
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Summary

The influence of temperature on the knee point and squareness of the M - H demagnetization characteristic of permanent magnets is important information for the full utilization of the capabilities of samarium-cobalt magnets at high temperatures in demagnetization-resistant permanent magnet devices. Composite plots of the knee field and the demagnetizing field required to produce a given magnetic induction swing below remanence were obtained for several commercial $\text{Sm}_2\text{Co}_{17}$ -type magnet samples in the temperature range of 23 to 300 °C. The knee point was used to define the limits of operation safe against irreversible demagnetization, and the resulting plots are interpreted to show the temperature-induction swing limits of safe magnet operation. The observed second quadrant M - H characteristic squareness is shown, by two measures, to increase gradually with temperature and to peak in the interval 200 to 300 °C.

Introduction

Of the various available high-energy permanent magnet materials, only the SmCo_5 and $\text{Sm}_2\text{Co}_{17}$ types can produce magnets retaining at 300 °C a useful remanence ($B_r \sim 0.9$ T) and a sufficiently high intrinsic coercivity ($MH_c > B_r$) to avoid self-demagnetization and to keep the induction (B) roughly linear with the applied field (H) in the second quadrant (refs. 1 to 4). Temperatures exceeding 250 °C are now being investigated for the exciting magnets to be used in linear alternators for long-term space missions (ref. 5) and may be expected as well for magnets to be used in future miniaturized devices, traveling wave tubes, and other particle beam applications. Several of these are cases of low-lying magnetic load line, where additional transient applied fields (e.g., due to motor start/stall or generator load fault currents) can combine with the effects of high temperature to create a demagnetizing influence severe even for the modern high-coercivity, rare earth-cobalt magnets. The present experimental work investigates the effect of high temperature on certain magnetization parameters and suggests plots to help one assess the margin of safety against irreversible loss of remanent magnetic moment (M_r). Since various magnet performance criteria, such as $(BH)_{\max}$, MH_c , and possibly the temperature stability of the "second-generation" 2-17-type magnets, generally exceed those of the 1-5-type, this investigation is restricted to the former.

Irreversible Demagnetization: Knee Point and Loop Squareness

An often used, if somewhat facile, definition of the point of onset of rapid downslope, or knee point, in the M - H characteristic in its second quadrant is where $M = 0.9 M_r$. Depending on the M - H loop squareness, rapid loss of remanent moment can set in if the applied field drives M below its knee point. As temperature increases, the knee field (MH_k) of high- MH_c , rare earth-cobalt magnets decreases in magnitude and will eventually appear as a knee in the second quadrant of the B - H characteristic. As temperature is increased for magnets operating statically on a low-lying load line, of say $B/H \sim -0.5$, the knee point will eventually cross to the right of the load line. The consequent immediate and irreversible (but recoverable by remagnetization) loss of remanence has been described in a number of early works (refs. 6 to 8). Even if operation is confined to the right of the knee point, close approach to the knee is likely, from energy considerations, to increase the rate of long-term magnetic aging. This sort of recoverable irreversible loss of magnetization, as opposed to irrecoverable loss due to metallurgical changes, may be caused by the thermal agitation of domain walls over their pinning potential barriers (ref. 8). Aside from these risks of demagnetization, swinging the B -field down close to its knee value may accentuate recoil-loop hysteresis loss (ref. 9), which is of concern in high-efficiency alternator applications. These considerations mark the knee point as important information for use in designing demagnetization-resistant permanent magnet devices.

Frequently, in dynamic applications of permanent magnets, their degree of utilization or magnetic stressing is specified by their swing ΔB of induction below B_r . However, the short-term irreversible losses depend on the difference, at a given temperature, between the highly temperature-sensitive MH_c or MH_k and the internal demagnetizing field (refs. 6, 7, and 10). Therefore, it is expedient to translate the minimum induction $B_r - \Delta B$ attained in a dynamic application to the corresponding peak demagnetizing field H_d by means of the constitutive relation $B(H) = H + 4\pi M(H)$ (cgs units) at temperature. At a given temperature and ΔB , H_d and MH_k can be compared for an estimate of the margin against irreversible loss of moment. These relations and definitions are illustrated in figure 1.

Squareness of the M - H hysteresis loop is at least a qualitative measure of the extent of the expected immediate loss of

magnetization in case M is driven below M_k by $|H_d| > |M H_k|$. For squareness, we shall consider the simple quotient $S = M H_k / M H_c$ and compare it with the more complicated "fullness factor" $F = (M H)_{\max} / (M_r M H_c)$. Note that a perfectly square loop has $S = F = 1$. A loop with vertical sides and a sloping top and bottom, which is a parallelogram and, hence, not strictly square, can have $S = 1$. However, in such a case the consequences of $|H_d| > |M H_k|$ are the same as for a square loop.

Experimental Apparatus and Method

The quasi-static demagnetization characteristics of commercial 2-17 type magnet samples were measured by an electromagnet-driven hysteresigraph. This apparatus is an improved, 300 °C model of a temperature-control and probe-coil assembly for magnet testing developed originally at the University of Dayton (ref. 11). In our apparatus, a precision 1-cm cubic magnet sample fits closely between the flat and parallel faces of iron-cobalt pole pieces that are rigidly mounted to an aluminum housing comprising the temperature control oven. These pole pieces serve as electromagnet pole piece extensions and are thermally insulated from the electromagnet pole pieces by 30-mil-thick PTFE shims. This fixture has tolerances and controlled overall thermal expansion such as to keep the effects of the sample-to-poleface gap negligible. The B -flux is sensed by a coil surrounding the sample, and the H -flux is sensed by another coil, of nearly the same area-turns and thermal expansion, located adjacent to the B -coil. After electronic integration, the signals from these coils are subtracted so as to air-flux compensate the B -coil, resulting in a signal proportional to the intrinsic magnetic moment M within the B -coil.

Absolute calibration of the M -axis, which could be done near room temperature only, was referenced to a pure nickel standard in the form of a 1-cm cube that has a known magnetic moment of 6.100 kG in an applied field of 10 kOe at 25 °C. Up to about 200 °C, the H -axis was calibrated by transfer from a precision reference permanent magnet by using a Hall effect probe. The absolute accuracy of these calibrations is estimated to be within ± 1 percent.

Prior to any measurement, the sample was twice pulse-magnetized open circuit at room temperature in a coil providing a 100-kOe peak field. Then, for measurements at 200 °C and above, the sample was preheated for approximately 5 min to about 100 °C below the measurement temperature in order to minimize chipping caused by thermal shock. Next, the sample was inserted into the preheated fixture and allowed to stabilize at the final temperature for a few minutes, after which the demagnetization curve was taken. No sample was ever soaked at the measurement temperature for more than 10 min. Since the probe-coil fixture, which holds the sample and the thermocouple, suffers unavoidable loss of heat during its

removal from the oven for magnet insertion, the accuracy of the magnet temperature reading was likely to be no better than ± 3 °C.

Observed Temperature Dependence of $M H_k$, H_d , S and F

Following the experimental procedure just described, demagnetization curves were taken for 10-sample groups of high- $M H_c$, anisotropic 2-17-type magnets from several manufacturers. Figure 2 illustrates the typical variation of demagnetization characteristics with temperature observed for this type magnet: the usual rapid loss of coercivity and relatively lesser loss of remanence as the temperature increases are exhibited. Since within each group the scatter of data was relatively small, a single sample was chosen to represent the group. Values of $M H_k$ and H_d at selected ΔB derived from the demagnetization curves at temperature are presented in figure 3 from room temperature to 300 °C for three such representative samples.

Inspection of the families of H_d curves parametrized by $\Delta B/B_r$, where B_r is at the test temperature, shows similar behavior for the three samples. For a fixed $\Delta B/B_r$ and temperatures to 200 °C, H_d decreases gradually with increasing temperature at a rate of about 4.5 Oe/°C. Above 200 °C, the downslope steepens with both increasing temperature and ΔB as a consequence of the knee-associated nonlinearity encroaching into the second B - H quadrant. Differences among the groups in H_d behavior become more pronounced at the higher temperatures and ΔB because the $M H_c$ generally displays greater sensitivity to temperature and sample source (variations in heat treatment and composition) than does B_r .

For all samples tested, $M H_k < B H_c \equiv H_{d,1}$ at room temperature; that is, the knee point was to the left of the B -coercivity point. However, the $|M H_k|$ generally decreases faster with rising temperature than does $|H_d|$, thus intersecting the H_d family of curves and defining a segment of the border of an unsafe region of operation, where $|H_d| > |M H_k|$. For example, considering temperatures up to 300 °C and ΔB up to B_r , this condition defines such unsafe regions of already substantial size in all three cases shown in figure 3. The considerable variation in size of these curvilinearly triangular regions is caused primarily by variations in the $M H_k$ curves.

Both squareness S and fullness F were computed for the M - H demagnetization curves of the three samples and are compared in figure 4. The S and F of these samples increase gradually when the temperature increases from room temperature to about 250 °C. A tendency for peaking in the 200 to 300 °C interval is also apparent for both measures. However, the S exhibits a somewhat more pronounced variation with temperature and sample and is more consistently ordered in height over the temperatures shown. Above 200 °C the relative ordering of the samples becomes the same by either S or F .

This ordering is not consistently correlated with IG6 receiving top rating, according to figure 3, for resistance to demagnetization at high temperatures.

Summary of Results and Conclusions

Quasi-static demagnetization curves were obtained from room temperature to 300 °C for 10-sample groups of high-coercivity, anisotropic, 2-17-type magnets from several manufacturers. Their resistance to short-term demagnetization was evaluated by a comparison, at a given temperature, of the knee field MH_k needed to reduce the magnetization to 0.9 of the remanence M_r and the demagnetizing field H_d needed to produce a desired swing ΔB of induction below remanence. A necessary condition for safe operation is assumed to be $|H_d| \leq |MH_k|$, where at equality the margin of safety vanishes.

Unsafe regions of operation of substantial size and variability by sample manufacturer appear when considering the effects of temperatures up to 300 °C and swings ΔB as large as B_r . For example, the sample rated most resistant to demagnetization has no margin left at 280 °C and $\Delta B = 0.9B_r$, whereas the least resistant sample has vanishing margin already at 240 °C for the same ΔB . Even at 250 °C, none of the magnets tested can safely sustain a $\Delta B = B_r$. These findings are apparent from the given composite plots of H_d for various ΔB and MH_k as a function of temperature. Furthermore, these plots show that room-temperature performance, such as a high MH_k , is not a reliable predictor of performance at high temperatures because slopes with temperature and their variability may be considerable. In this way, such composite plots can be very useful for providing comparative overviews of the temperature-induction swing limits of safe magnet operation.

Since the amount of magnetization loss resulting from an excursion into an unsafe region is directly related to the M - H hysteresis loop squareness in the second quadrant, two measures of squareness were compared for representative samples from the several groups. One measure is the fullness factor ($F = (MH)_{\max}/(M_r MH_c)$) and the other is the squareness ($S = MH_k/MH_c$). These properties exhibit a gradual increase with temperature, reaching a peak in the interval 200 to 300 °C. The S , however, had a more pronounced variation with temperature and sample source. In either case, no simple

relation could be discerned to the ranking of samples by the safe region criterion. Nevertheless, further study of both S and F may be warranted in that using 2-17-type magnets above 250 °C in electromechanical devices may force magnet operation close to the knee point of maximal squareness.

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Cleveland, Ohio, April 12, 1991

References

1. Wallace, W.E., et al.: Synthesis of High Energy Magnet Materials: Coercivity Mechanism, Surface Studies and New Alloys. *Mater. Sci. Eng. B*, vol. 3, 1989, pp. 351-354.
2. Potenziani, E., II, et al.: The Temperature Dependence of the Magnetic Properties of Commercial Magnets of Greater than 25 MGOe Energy Product. *J. Appl. Phys.*, vol. 57, no. 8, pt. IIB, Apr. 15, 1985, pp. 4152-4154.
3. Magnetic Materials. Committee on Magnetic Materials, National Materials Advisory Board, NMAB-426, National Academy Press, 1985. (Avail. NTIS, AD-A154679).
4. Strnat, K.J.: Study and Review of Permanent Magnets for Electric Vehicle Propulsion Motors. NASA CR-168178, DOE/NASA/0189-83/2, 1983.
5. Slaby, J.G.: Free-Piston Stirling Technology for Space Power. NASA TM-101956, 1989.
6. Bachmann, K.: Reversible and Irreversible Losses of Magnetization in SmCo_5 -Magnets. *Magnetism and Magnetic Materials*, C.D. Graham, Jr. and J.J. Rhyne, eds., AIP Conf. Proc. No. 18, Pt. 2, 1973, pp. 1168-1172.
7. Martin, D.L.; and Benz, M.G.: Magnetization Changes for Cobalt-Rare-Earth Permanent Magnet Alloys when Heated up to 650 °C. *IEEE Trans. Magn.*, vol. 8, no. 1, Mar. 1972, pp. 35-41.
8. Mildrum, H.F., et al.: An Investigation of the Aging of Thermally Prestabilized Sintered Samarium-Cobalt Magnets. *IEEE Trans. Magn.*, vol. 10, no. 3, Sept. 1974, pp. 723-725.
9. Qishan, G.; and Lin, C.: Field Computation of Permanent Magnets with Knee Points. *IEE Proc. Pt. B, Elect. Power Appl.*, vol. 136, no. 6, Nov. 1989, pp. 275-279.
10. Martin, D.L.: Permanent Magnet Characterization Measurements. *Proceedings of the Fifth International Workshop on Rare Earth-Cobalt Permanent Magnets and Their Applications*, K.J. Strnat, ed., University of Dayton, 1981, pp. 371-404.
11. Mildrum, H.F.; and Graves, Jr., G.A.: High Speed Permanent Magnet Generator Material Investigations—Rare Earth Magnets. Air Force Wright Aeronautical Laboratories, AFWAL-TR-81-2096, Oct. 1981. (Avail. NTIS, AD-108550).

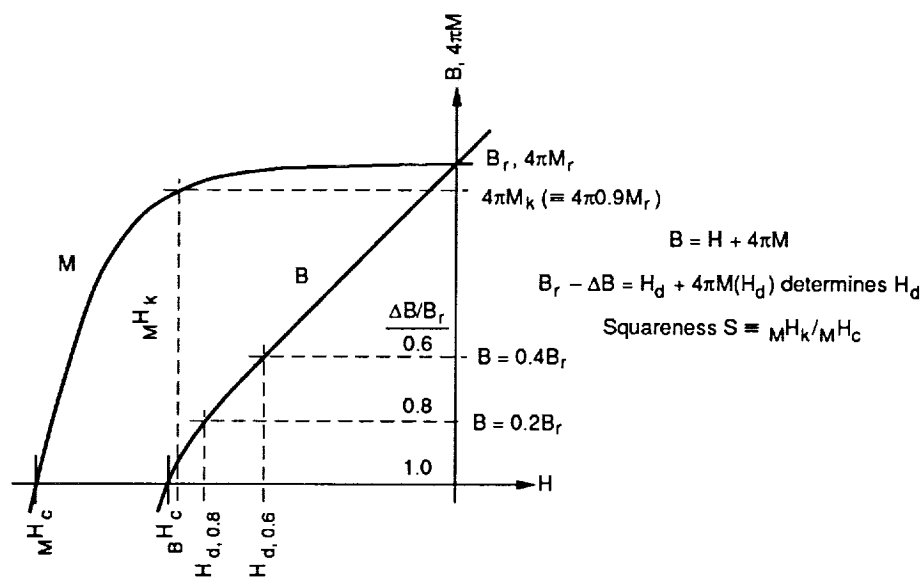


Figure 1.—Illustrations of definitions and the increase in magnitude of the demagnetizing field H_d for increasing $\Delta B/B_r$.

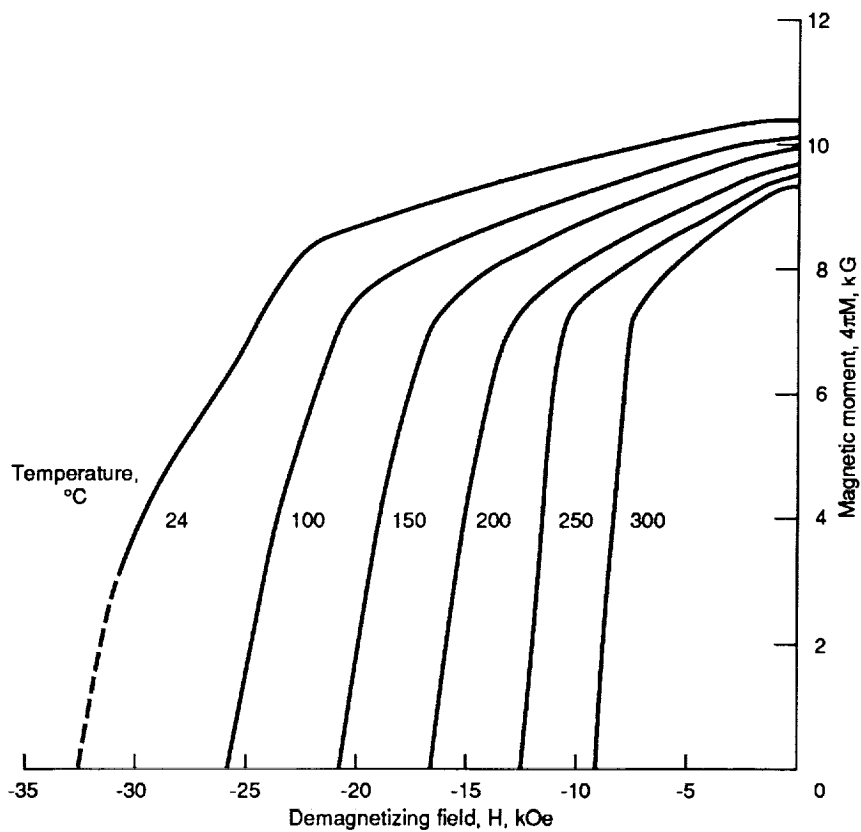
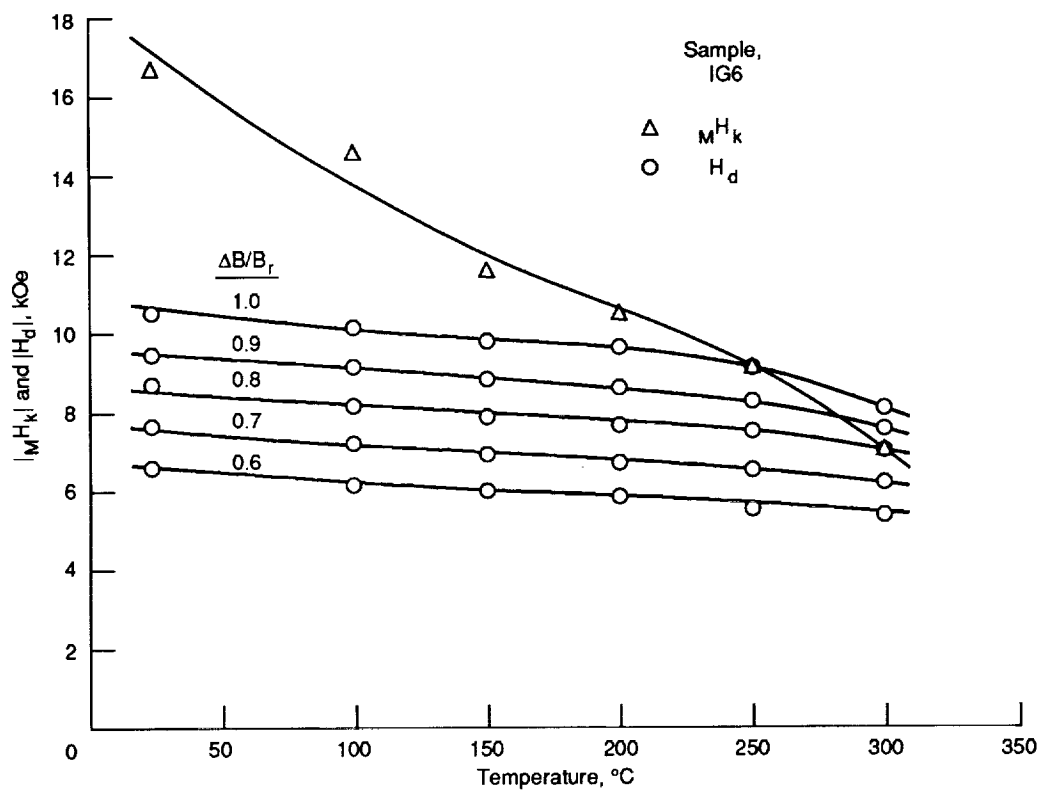
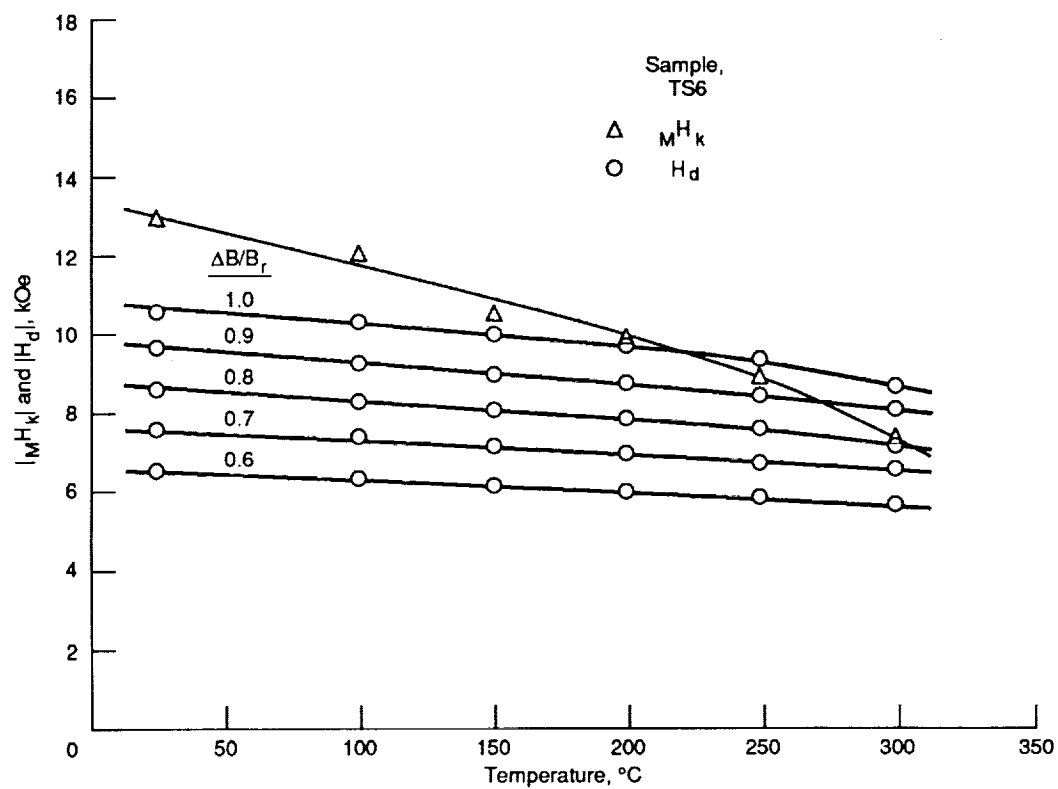


Figure 2.—Demagnetization characteristics of sample IG6 at selected temperatures to 300 °C. A pronounced M - H curve top droop was observed for all 2-17-type samples tested.



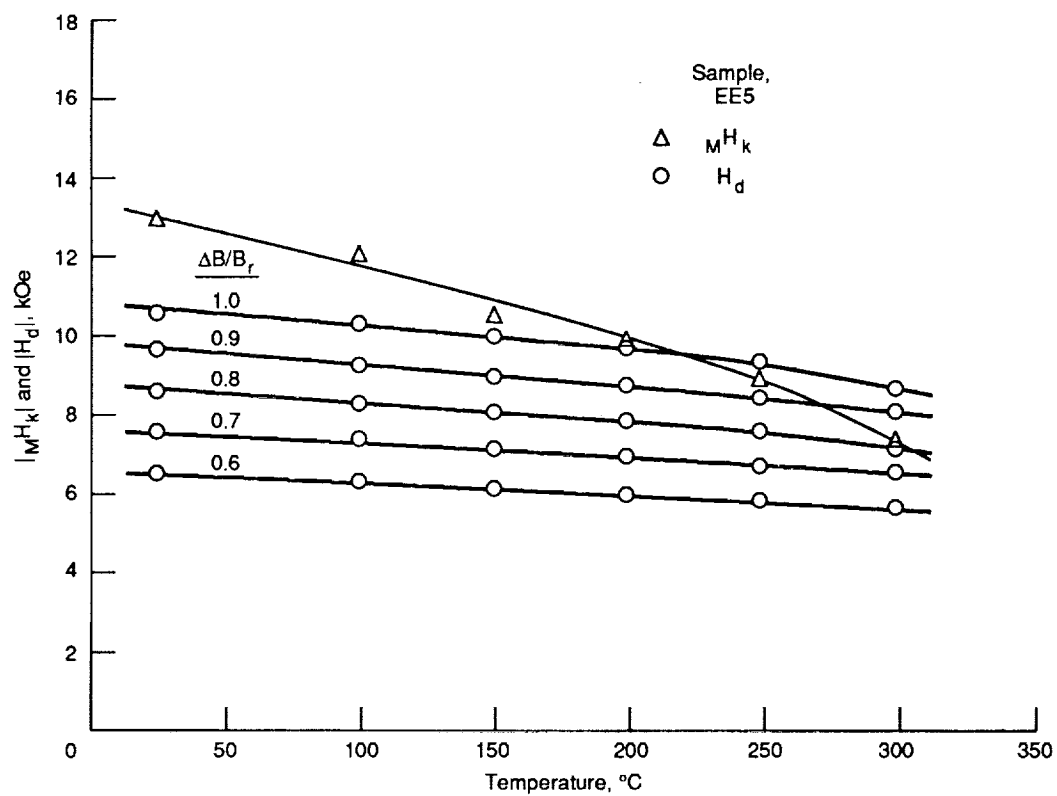
(a) A very high room-temperature M^H_k makes this IG group the most resistant to demagnetization at high temperatures in spite of the high room-temperature dM^H_k/dT .

Figure 3.—Temperature variation of the knee field (M^H_k) and the demagnetizing field (H_d) for selected induction swings of 2-17-type samarium-cobalt magnet samples.



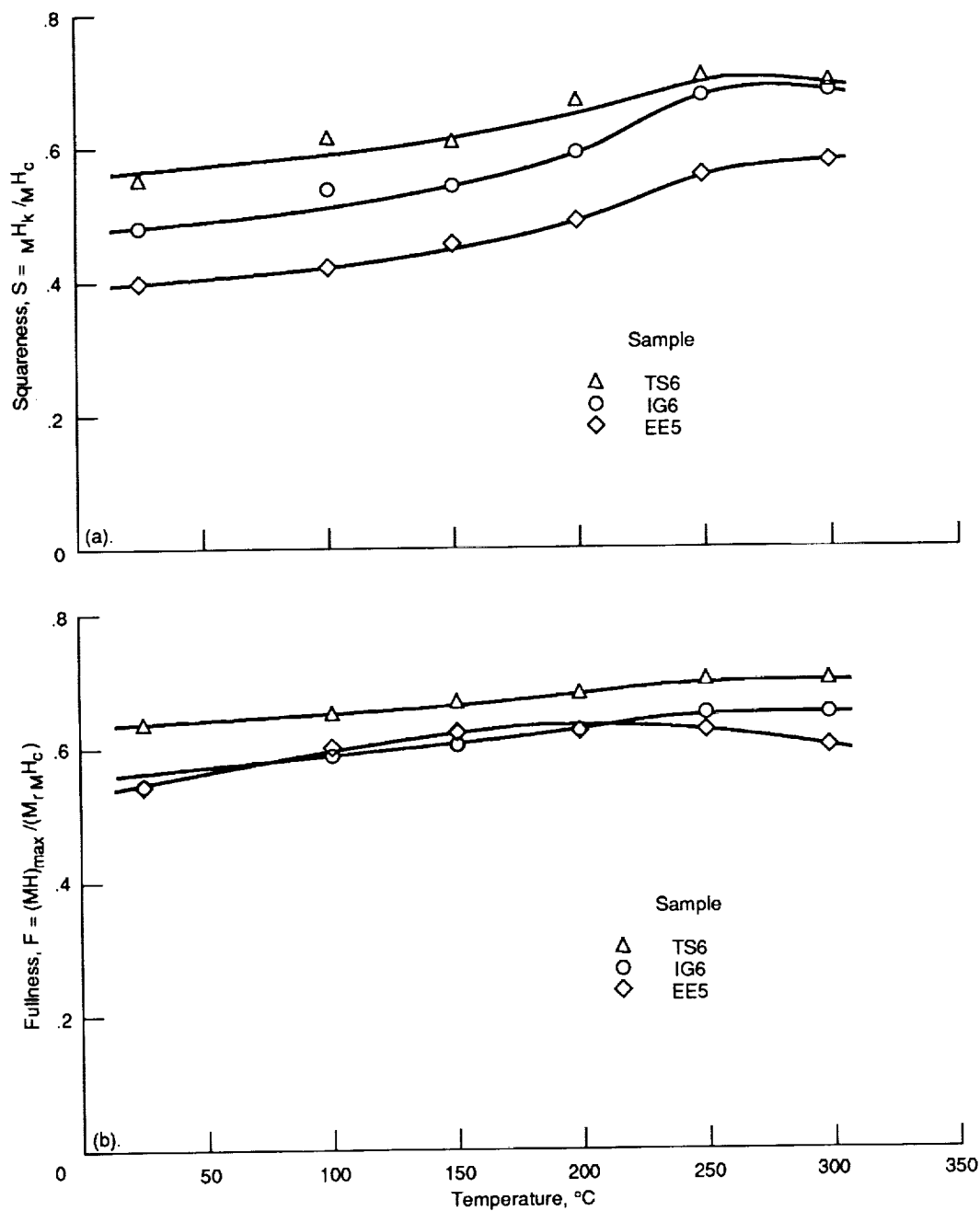
(b) A low $d_M H_k/dT$ compensates for the rather low room-temperature M^H_k of the TS group (sufficiently to give it second place).

Figure 3.—Continued.



(c) The benefit of a moderately high initial M^H_k of the EE batch is lost at high temperatures because of a high $d_M H_k/dT$.

Figure 3.—Concluded.



(a) The S factor exhibits a sharper peaking with temperature and a better sample resolution.
 (b) F is generally less sensitive to temperature and sample source but resembles S above 200°C .
 Figure 4.—Comparison of the squareness (S) and fullness (F) as a function of temperature.

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